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Study of C, N, P and K Release from Residues of Newly Proposed Cover Crops in a Spanish Olive Grove

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Abstract: Cover crops (CC)s are increasingly employed by farmers in olive groves. Spontaneous soil cover is the most commonly used CC. Its continuous utilization changes ruderal flora. It is necessary to study new CCs. Living CCs provide C and nutrients to soil during decomposition. Information on this issue in olive groves is scarce. A 4-year field study involving grab sampling of *Brachypodium distachyon*, *Sinapis alba* and spontaneous CC residues was conducted to study C and nutrient release from cover crop residues. Throughout the decomposition cycles, C, N and P release accounted for 40 to 58% of the C, N and P amounts in the residues after mowing. Most K was released (80–90%). Expressed in kg per hectare, the release of C and N in *Brachypodium* (C: 4602, N: 181, P: 29, K: 231) and *Sinapis* (C: 4806, N: 152, P: 18, K: 195) was greater than that in spontaneous CC (C: 3115, N: 138, P: 21, K: 256). The opposite results were observed for K. The Rickman model, employed to estimate the amount of C, N and P in residues, yielded a good match between the simulated and measured values. In comparison to spontaneous CC, the newly proposed CCs have a higher potential to provide soil with C and N.

Keywords: cover crops; olive grove; decomposition model; nutrient release; nitrogen; carbon; phosphorus; potassium; *Sinapis alba*; *Brachypodium distachyon*

1. Introduction

The Mediterranean basin accounts for 95% of the global area of olive (*Olea europaea* L.) trees [1]. It is the main tree species among those cultivated in the Mediterranean area and dominates its rural landscape [2]. Spain has the highest production and surface area in the world, with 2.73 Mha [3], and over 60% of the olive production in the European Union. This production has continued to grow over the last 20 years. Andalusia has 1.63 Mha of olive groves [3], so the importance of this crop in this region is highly significant.

The Mediterranean climate is characterized by very hot and dry summers and a gap in precipitation in this season; moreover, the inter-annual and intra-annual variability in rainfall is high, with droughts and intense rainfall events [4]. Olive trees are well adapted to these conditions and are not particularly demanding in terms of water and nutrients. For this reason, they have been cultivated traditionally in marginal areas of low fertility, steep slopes and shallow soils [5].

Olive trees are planted leaving an unprotected alley between them to let their roots capture water and nutrients in the soil. Their canopy normally provides less than 35% of soil cover in conventional plantations [6,7]. To prevent any competition for nutrients with other plants and since olive trees are mostly rainfed, farmers usually control weeds by tillage [8].

Such tillage has accelerated soil organic matter losses and has disrupted the soil structure, increasing erosion [9]. Mediterranean soils are susceptible to degradation due to the reduction in organic matter [10]. Organic matter is essential for soil fertility and it improves soil structure [11].

The introduction of alternative soil-management practices, such as spontaneous or cultivated cover crops (CC)s along the inter-rows of olive trees, has proven to be an efficient tool to reduce erosion, runoff and soil fertility loss [6,12–14]. Gramineous species were initially recommended to farmers because of their good ground protection, relatively low competition with olive trees and easy use and control [15].

Nevertheless, most olive growers use spontaneous vegetation due to economic savings in seed. In 2018, 92% of the Spanish olive grove areas with any type of CC had a spontaneous CC [16] that was occasionally combined with mulch cover of pruning residues, which are durable, protect the soil and enhance soil fertility [17–20]. However, the continued use of the same CC produces a change in ruderal flora. This drawback can make CC management harder for farmers in the medium term. One option is to use multispecies mixes [21]. However, this kind of CC requires very careful management by the farmer because the species that make up the CC have different growth cycles and responses to herbicides or mowing.

Thus, Alcántara et al. [22] suggested the use of an interannual rotation of CCs, where each CC can fulfil a different and complementary role. Two species being studied for use in Andalusian olive groves are *Brachypodium* (*Brachypodium distachyon* L. Beauv. (Poaceae)) and mustard (*Sinapis alba* L. subsp. *mairei* (H. Lindb. Fil.), hereafter referred to as *Sinapis* or common mustard). These two species have very different characteristics. *Brachypodium* is a short-cycle grass. Its main role is the control of soil erosion since it has a great potential to produce a high biomass amount. This CC has been recently studied for its use in vineyards in Spain [23]. On the other hand, *Sinapis* and other crucifer species have multiple benefits, such as the control of soil compaction due to its tap root [24], control of *Verticillium dahliae* [25] and soil loss reduction [26]. Unlike grass and spontaneous vegetation, *Sinapis* is sown yearly to ensure good nascence.

CCs can play an important role in increasing soil organic matter and soil nutrients. In this sense, farm strategies should maximize crop residue return to the soil to enhance its quality [27]. There is very scarce information on the nutrient release from aboveground residues during the decomposition of CCs in olive groves. Research on nutrient release has usually been performed in arable crops with no-till systems [28,29]. Some works have considered only the living stage of CCs [30]. It seems insufficient to assess nutrient recycling since nutrients retained by CCs will be available in the decomposition period after mowing [31]. Gómez-Muñoz et al. [32] compared nutrient release from legumes and ruderal species in a one-year study period in an olive grove, but crucifers or grass CCs were not tested. There is a clear lack of information regarding nutrient release in these newly and recently proposed cover crops, such as *Brachypodium* and *Sinapis*. Similarly, since intra-annual conditions can change substantially, it is necessary to properly characterize nutrient release from *Brachypodium* and *Sinapis* in a multi-year study, as in this case.

Additionally, studies on decomposition are usually performed in the laboratory or in the field with the mesh bag technique. However, as reported by Ruffo and Bollero [33], a more realistic method is needed. In fact, litterbags have three main problems. First, they alter the microclimate of the residues. Second, litterbags modify access to the residues of the decomposers. In this sense, Tian et al. [34] obtained a positive correlation between mesh size and decomposition rate. Third, litterbags put a fraction of the residues in contact with the soil. Under natural conditions, part of the residues would be standing [35]. For the abovementioned reasons, Bokhorst and Wardle [36] indicated that using litterbags could disturb the decomposition process in residues in comparison with residues laying

directly on the surface under natural conditions. Grab sampling, used in this study, involves a more realistic situation even though it involves more field work and greater variability in the obtained data due to natural field variation at short distances [37,38].

Decomposition characterization is important for the sustainable management of a field, especially in conservation agriculture. Residue decomposition can be described through modelling, which considers the main biotic and abiotic parameters that influence the process, such as soil moisture, C/N ratio, air temperature and N concentration in the residues [39–41]. The model of Douglas and Rickman [39] and the model of Rickman et al. [40]—referred to here as the Rickman model—are based on first-order decay equations and have a low data requirement. Both have proven to be useful to predict residue decomposition under Mediterranean conditions [42,43], as well as in a wide range of climates [44]. These models are currently used alone or as part of more complex soil models [41,45,46].

Modelling the C, N, P and K release of the residues of a proposed CC can help us to determine its capacity to provide these elements to the soil. Additionally, knowledge of nutrient release, in addition to the variation in the residue density in a field, could be useful to design management zones in the future to implement on-site nutrient applications [47]. The purpose of this research was to test the hypothesis that the residues of these newly proposed CCs can release more C, N, P and K amounts than the spontaneous CC, and to check if nutrient release can be accurately characterized with simple models.

The aims of this study were (i) to assess the C, N, P and K release in a 4-year field study from newly proposed species (*Sinapis alba* and *Brachypodium distachyon*) that could be potentially recommended in the short term as CCs in olive groves and from controlled spontaneous vegetation as a control and (ii) to evaluate a decomposition model, determining its predictive ability to ascertain C, N, P and K release from the studied CC residues.

2. Materials and Methods

2.1. Site and Experimental Design

The experiments were conducted at the Arenillas rainfed Picual olive grove farm in Fernán Núñez (Córdoba, Spain) during four growing seasons (2008–2011). The plot was located at 37°40′1.53″ N, 4°47′ W and 266 m above mean sea level. It had an 11% average slope. The soil was a *Vertic haploxerept* [48], whose main physicochemical characteristics are shown in Table 1.

Table 1. Physicochemical characteristics of the soil.

Depth (cm)	Sand (%)	Silt (%)	Clay (%)	OM (%)	CO ₃ = (%)	N (%)	P (mg kg ^{−1})	K (mg kg ^{−1})	CEC (mol _c kg ^{−1})	pH (H ₂ O)	pH (CaCl ₂)
0–10	6.0	43.5	50.5	0.85	29.9	0.04	6.5	326.2	0.24	8.1	7.7
10–20	9.8	39.4	50.8	0.72	28.5	0.03	13.6	369.5	0.22	8.2	7.7
20–40	8.4	41.7	49.9	0.65	31.8	0.02	9.9	271.8	0.23	8.3	7.7
40–60	8.8	41.8	49.4	0.58	33.1	0.02	11.0	209.7	0.22	8.4	7.7

OM: Organic matter; N: Total nitrogen; P: Available phosphorus; K: Exchangeable potassium; CEC: Cation exchange capacity.

This area has a typical Mediterranean climate, with three to five hot and dry months (June to September). Rainfall and daily temperature data were recorded during the four years of the study (Figure 1) at a weather station belonging to the agricultural weather station network (RIA) of the Consejería de Agricultura y Pesca (Junta de Andalucía).

The olive trees were eighteen years old and were planted at a distance of 8 m between the rows and 4 m between trees in the row. A randomized complete block design with five replications and four subsamples per experimental unit was adopted. The blocks were arranged perpendicularly to the slope. The experimental unit was a CC strip of 12 m × 4 m.

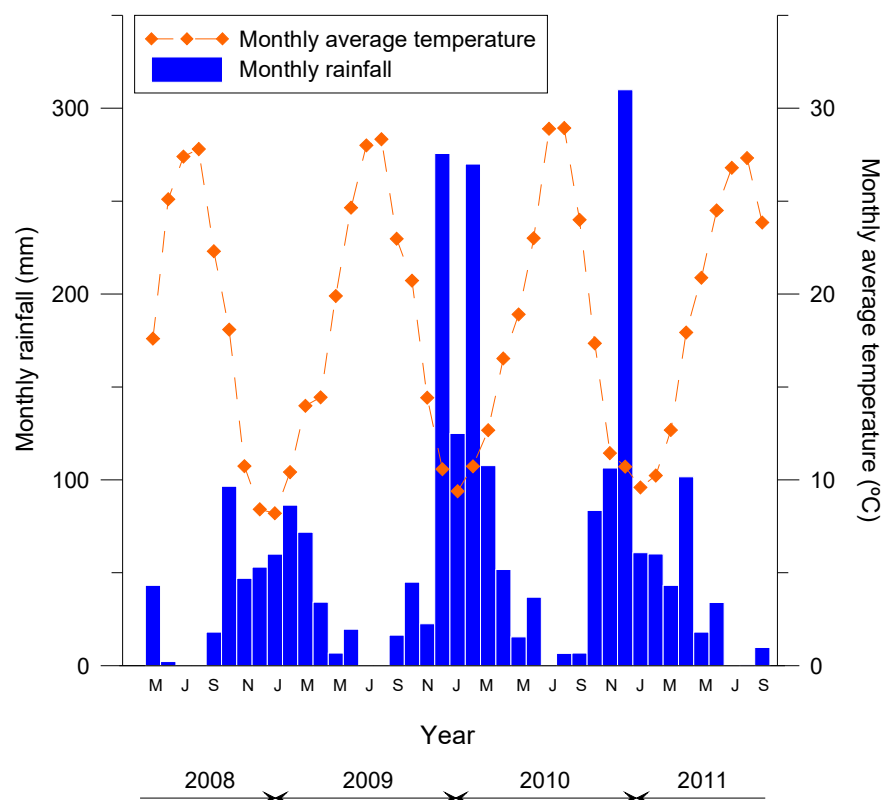


Figure 1. Monthly rainfall and monthly average temperature in the research area from May 2008 to September 2011.

Three CCs were employed in the field trials. The first CC was *Brachypodium distachyon* L., a sown-grass CC commercially called Vegeta, while the second CC was the cruciferous species *Sinapis alba* L. subsp. *mairei* (H. Lindb. Fil.), commonly called maire or common mustard, which was also sown. The third CC was spontaneous cover of typical ruderal plants of the area, mainly consisting of *Malva* spp., *Convolvulus arvensis* L., *Linaria vulgaris* Mill., *Diplotaxis virgata* (Cav.) DC., *Picris echioides* L., *Melilotus indica* (L.) All., *Medicago polymorpha* L., *Lolium rigidum* L. and *Taraxacum officinale* (L.) Weber.

Depending on the yearly weather conditions, the autumn sowing dates were from mid-October to late November (Table 2). Common mustard seeds were previously collected from spontaneous wild populations and were replicated in the Andalusia Research Centre IFAPA Alameda del Obispo (Córdoba, Spain). Cruciferous seeds were broadcasted yearly over the plot at rates of 10 kg ha⁻¹ without deep burying to improve emergence [22]. Every year, a disc-harrow pass prepared the seedbed just before the sowing of the crucifer and buried the remaining residues after each decomposition cycle.

Brachypodium was only sown the first year at a rate of 100 kg ha⁻¹ of commercial product, equivalent to 30 kg seeds ha⁻¹, following commercial recommendations. A disc-harrow plough pass was employed at the beginning of the experiment (Table 2). After the first year, *Brachypodium* was established from a CC strip that had been left alive the first year to sow itself in the following seasons.

The fertilization on the farm consisted of 200 kg ha⁻¹ of urea (46% N) spread in February every year. The experimental plots were not fertilized with P and K during the 4-year study period. The area under the canopy was treated with systemic herbicide to control the weeds. CCs were mowed with a commercial mower at a mean cutting height of 5 cm.

Table 2. Operations carried out in the experimental field.

Year	Date	Operations		
		<i>Brachypodium</i>	<i>Sinapis</i>	Spontaneous Soil Cover
1	22/10/07	Disc harrow Sowing	Disc harrow Sowing	Disc harrow
	31/03/08	Drag tine harrow	Drag tine harrow	
	07/05/08	Mowing Mowing	Mowing Mowing	Mowing Mowing
2	25/11/08	†	Disc harrow Sowing	†
	03/04/09	Mowing	Drag tine harrow	
	07/05/09	Mowing	Mowing Mowing	Mowing Mowing
3	30/11/09	†	Disc harrow Sowing	†
	24/03/10	Mowing	Drag tine harrow	
	03/05/10	Mowing	Mowing Mowing	Mowing Mowing
4	04/11/10	†	Disc harrow Sowing	†
	22/03/11	Mowing	Drag tine harrow	
	10/05/11	Mowing	Mowing Mowing	Mowing Mowing

†: self-seeding.

2.2. Sampling Scheme

Samplings were conducted every year after mowing the CCs. From that date forward to the autumn sowing in the new growing season, residues were periodically sampled (Table 3). The residue mass was estimated from the stubble collected in a 0.25-m² metal frame, which served to delimit the sampling area. Four random residue-collection points were established per experimental unit. The residue collected was sent to the laboratory where it was washed with distilled water to prevent contamination in the subsequent analysis. Then, it was placed in an oven at 65 °C until it reached a constant weight, and it was possible to estimate the amount of dry matter.

Table 3. Sampling dates in the studied cover crops.

Species	Year	Dates						
<i>Brachypodium</i>	1	13/05/08	03/06/08	27/06/08	11/07/08	28/08/08	25/09/08	16/10/08
	2	11/05/09	09/06/09	25/06/09	16/07/09		16/09/09	29/10/09
	3	10/05/10	15/06/10		30/07/10		22/09/10	19/10/10
	4		15/06/11			22/08/11	13/09/11	
<i>Sinapis</i>	1		03/06/08	27/06/08	11/07/08	28/08/08	25/09/08	16/10/08
	2			25/06/09	16/07/09	27/08/09	16/09/09	29/10/09
	3	10/05/10	15/06/10		30/07/10	24/08/10	22/09/10	19/10/10
	4		15/06/11			22/08/11	13/09/11	
Spontaneous	1				11/07/08	28/08/08	25/09/08	16/10/08
	2				16/07/09	27/08/09	16/09/09	29/10/09
	3	10/05/10	15/06/10		30/07/10		22/09/10	19/10/10
	4		15/06/11			22/08/11	13/09/11	

2.3. Analysis of Samples

Total C and total N in the residue samples were analysed in a LECO elemental analyser (TRUSPEC, CNS; St. Joseph, MI, USA). Total P content in the residues was determined by colorimetry and total K by atomic absorption spectrophotometry, both after converting the sample into ash and dissolving it in 100 mL hydrochloric acid (HCl) 0.1 N. The determination of soil organic matter was based on the Walkley-Black method. Total N in soil samples was analysed in the LECO elemental analyser; available P in soil was measured by colorimetry following the Olsen method, and exchangeable K was measured by atomic absorption spectrophotometry after extraction with NaHCO_3 0.5 M and $\text{CH}_3\text{COONH}_4$ 1 M, respectively. The particle size distribution of the soils was determined by the densimeter method after dispersion with sodium hexametaphosphate. Soil pH was measured with a glass electrode using a 1:2.5 extractant solution.

2.4. Data Analysis

2.4.1. C, N, P and K Release from Residues

The residual amounts (Mg ha^{-1}) of carbon, nitrogen, phosphorus and potassium remaining at each aboveground residue sampling were calculated using the product of the dry matter of the residues by the concentration of the corresponding element on the sampling date.

The C, N, P and K release from the different CC residues was calculated, understanding as such the difference between the content of this element in the residues when no regrowths were registered and that estimated in the residue samples collected on the different dates, according to the Equation (1):

$$\text{Release} = y_0 - y_t \quad (1)$$

where y_t (Mg ha^{-1}) is the amount of C, N, P or K remaining in the residue at time t , and y_0 (Mg ha^{-1}) is the amount of each element remaining in the first sampling.

2.4.2. C, N and P Modelling

The Rickman model was used to assess the decomposition of the aboveground CC residues. This model assumes a first-order decay with respect to degree-days, in accordance with the following Equation:

$$M_{t+1} = M_t \exp(-k \cdot f_N \cdot f_w \cdot f_X \cdot f_B \cdot \text{DGD}_t) \quad (2)$$

with M_{t+1} and M_t : residue mass (kg ha^{-1}) in the days $t + 1$ and t , respectively; DGD_t : degree-days on the day, taken as an average daily temperature (over 0°C), and k is a rate coefficient ($^\circ\text{C}^{-1}$). The factors f_N and f_w consider the amount of initial N in the residue and the effects of the moisture content. For the calculation of the factor f_N , the regression shown in Douglas and Rickman [39] was used:

$$f_N = 0.57 + 0.126[\text{N}] \quad (3)$$

where $[\text{N}]$ is the initial N concentration in the residue (g N kg^{-1}), and 0.2 is the value of f_w used [44]. f_X and f_B are a soil texture index and a biomass or residue type factor, respectively. Their values were set to 1, according to Rickman et al. [40]. The model was also employed to predict the decomposition of the roots in *Brachypodium* and *Sinapis*, with $f_B = 0.35$ and $f_w = 0.8$ [40]. Following Chochois et al. [49], it was assumed that roots in *Brachypodium* account for 59% of total dry weight. Regarding *Sinapis*, Hajzler et al. [50] reported a root/shoot ratio of 0.32. This value was employed for the modeling. The concentration of N in the roots was taken as 1.75% in *Sinapis* [51] and 3% in *Brachypodium* [52].

Once the Rickman model was calculated, the amount of remaining C in the residue was obtained from Equation (4):

$$\text{Residual } C_{i,t} = \alpha + \beta \times \text{Residue amount}_{i,t} + \varepsilon_{i,t} \quad (4)$$

where α and β are parameters, Residual $C_{i,t}$ is the amount of C (kg ha^{-1}) for sample i at instant t —calculated by multiplying the dry matter amount by its corresponding C concentration—and Residue amount i,t is the amount of residue (kg ha^{-1}) for sample i at instant t . This approach was used since the C concentration in the residues was very constant throughout the decomposition cycles.

A relplot [53] was used to detect outliers in Equation (4). Details of the calculation can be found in Wilcox [54]. Equation (4) was calculated using the least-trimmed-squares (LTS) regression, a robust statistical criterion for analysing regression data sets [55].

In terms of the N, P and K content in the residues, the prior approach could not be used since nutrient concentration varied over time. For each sample, the residual amounts of N, P and K were calculated by multiplying the dry matter amount by the concentration of every element.

For C, N, P and K, we used the 0.2-sample trimmed mean [Equation (5)] as a measurement of location to more accurately characterize the experimental amount in each sampling period due to the non-normality and high variability shown by the field data. In these cases, the sample mean estimates a non-robust measure of location [54].

The procedure to calculate the α -sample trimmed mean is described by Wilcox [54] as follows: (i) let $X_1, X_2, \dots, X_{n-1}, X_n$ be a random sample and let $X_{(1)}, X_{(2)}, \dots, X_{(n-1)}, X_{(n)}$ be the observations written in ascending order; (ii) suppose the desired amount of trimming has been chosen to be α ; let $k = [n \cdot \alpha]$, where $[n \cdot \alpha]$ is the value of $n \cdot \alpha$ rounded down to the nearest integer; (iii) the α -sample trimmed mean X_α is defined as:

$$X_\alpha = (X_{(k+1)} + \dots + X_{(n-k)}) / (n - 2k) \quad (5)$$

with $\alpha = 0.2$ in our case, thus representing the 0.2-sample trimmed mean.

The scale parameter employed was the standard error of the α -sample trimmed mean. The procedure to estimate the standard error of a trimmed mean based on a random sample of n observations is the following [54]: (i) winsorize the observations by transforming the i th observation, X_i to W_i using the Equation (6); (ii) Compute the sample variance of the W_i values, yielding s_w^2 , the winsorized sample variance; (iii) The standard error of the trimmed mean is estimated according to Equation (7).

$$W_i = \begin{cases} X_{(k+1)}, & \text{if } X_i \leq X_{(k+1)} \\ X_i, & \text{if } X_{(k+1)} \leq X_i \leq X_{(n-k)} \\ X_{(n-k)}, & \text{if } X_i \geq X_{(n-k)} \end{cases} \quad (6)$$

$$\text{Var}(x_\alpha) = s_w / [(1 - 2\alpha) \cdot n^{0.5}] \quad (7)$$

In order to get an average release rate for N (k_N), and P (k_P) and thus to characterize the whole study period, the experimental amounts of N and P were separately pooled and normalised every year. Later, we fitted a simple exponential model (Equation (8)).

$$\text{Normalised nutrient } t_{j+1} (\text{kg ha}^{-1}) = \text{Normalised nutrient } t_j (\text{kg ha}^{-1}) \exp(-k \cdot \text{DGD}_{t_j \text{ to } t_{j+1}}) \quad (8)$$

where $j + 1$ is the number of samples in every CC at the year t (t from 1 to 4), $\text{DGD}_{t_j \text{ to } t_{j+1}}$ is the total amount of degree days between the samplings j and $j + 1$, and k refers to k_N , k_P .

The decomposition constant k used for every type of CC and nutrient was determined through non-linear regression, employing the method of Levenberg–Marquardt. The split-sample technique [56] was used to evaluate the amount of residue predicted by the model both in calibration and validation. To check whether the simulations of nutrient amounts provided by the models were satisfactory, measurements (observations) were plotted against time, based on graphical comparison of model-predicted values with on-field measurements. This method provides a simple and qualitative way to assess if model predictions match actual data [57]. From a quantitative perspective, the efficiency of the different models was quantified using the coefficient of efficiency (E) of Nash and Sutcliffe [58] [Equation (9)] and the Pearson's linear correlation coefficient (r_{xy}) between simulated and observed values for every species throughout the sampling period. Additionally, the coefficient of residual mass

(CRM) [Equation (10)] was used to indicate a prevalent model overestimation or underestimation of the observed values [59].

The coefficient of efficiency is defined as:

$$E = 1 - \Sigma(O_i - P_i)^2 / \Sigma(O_i - \bar{O})^2 \quad (9)$$

where O_i and P_i are the observed and predicted values in any sampling period, respectively. CRM is calculated as:

$$CRM = (\Sigma O_i - \Sigma P_i) / \Sigma O_i \quad (10)$$

The values considered to be optimal for these criteria are 1 for r_{xy} and E and 0 for CRM. Following common practice, simulation results are usually considered good for values of E greater than or equal to 0.75, satisfactory for values of E between 0.75 and 0.36, and unsatisfactory for values below 0.36 [60].

Finally, no fit existed with the K content in the residues since leaching was the dominant process. For this reason, only the results regarding C, N and P are presented in the modelling.

2.4.3. Statistical Analysis and Software

A two-way analysis of variance with a blocking factor, five replications and subsampling ($n = 4$) was performed for the residue amount to explain the performance of the different CCs. The factors were type of CC and year (four levels: one through four). To determine decomposition rates (Equation (8)), non-linear regression was used. Statistical analyses were performed with the software SPSS v.23 (IBM, Armonk, NY, USA) and R [61]. To create the figures, we used Grapher version 12 software.

3. Results and Discussion

3.1. Residue Release of C, N, P, K

Of the three nutrients considered, N presented the highest mean proportion in the first sampling after mowing in all CCs (Table 4), with very similar mean values for *Brachypodium* (1.47%), *Sinapis* (1.46%) and controlled spontaneous vegetation (1.59%). After N, K was the main element, ranging between 1.15% (*Sinapis*) and 1.53% (controlled spontaneous vegetation). Finally, P was the less abundant element, with very similar percentages in the studied CCs (0.18% to 0.21%). Similarly, the percentages of C in the CCs were very similar, with values ranging from 39.5% (*Brachypodium*) to 40.1% (*Sinapis*). Carbon content values among herbaceous plants have been reported to be very similar, although, at the same time, variable among organs of a plant [62].

Table 4. Concentrations of C, N, P and K in the aboveground residues at the beginning of each decomposition cycle.

Cover Crop	Element (%)	Year				Average
		1	2	3	4	
<i>Brachypodium</i>	C	40.8 ± 1.1	41.7 ± 0.8	37.4 ± 3.0	39.7 ± 1.1	39.6 ± 0.4
	N	1.9 ± 0.3	1.3 ± 0.1	1.6 ± 0.5	1.1 ± 0.3	1.5 ± 0.1
	P	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.0	0.2 ± 0.0
	K	1.6 ± 0.5	1.6 ± 0.8	0.9 ± 0.9	0.6 ± 0.2	1.2 ± 0.1
<i>Sinapis</i>	C	41.5 ± 1.2	41.8 ± 1.9	38.4 ± 1.4	38.5 ± 1.7	40.1 ± 0.3
	N	1.2 ± 0.3	1.3 ± 0.2	2.2 ± 0.4	1.2 ± 0.2	1.5 ± 0.1
	P	0.1 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.2 ± 0.0	0.2 ± 0.0
	K	0.5 ± 0.5	0.6 ± 0.2	2.9 ± 1.0	0.5 ± 0.3	1.2 ± 0.2
<i>Spontaneous</i>	C	41.3 ± 1.1	40.7 ± 1.4	38.4 ± 1.5	38.4 ± 1.5	39.9 ± 0.3
	N	1.4 ± 0.4	1.5 ± 0.4	2.2 ± 0.4	1.2 ± 0.6	1.6 ± 0.1
	P	0.1 ± 0.0	0.2 ± 0.1	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.0
	K	1.9 ± 1.0	1.1 ± 0.5	2.7 ± 1.1	0.3 ± 0.1	1.5 ± 0.2

The values of N, P and K concentrations in the third year in *Sinapis* and controlled spontaneous vegetation were much higher than the corresponding values for the remainder of the study period (Table 4). Notably, the date of mowing varied among years, depending on CCs development (Table 2). The analysed vegetal material in the third year was very likely to be less senescent than that in the remaining years, which could cause the aforementioned differences. This scenario was not observed in *Brachypodium*.

The mean C/N values were similar to each other. This ratio influences the decomposition rate of plant residues [63]. Regarding this issue in the studied CCs, the scientific literature provides limited information. The mean C/N value for *Sinapis* was 27.3, in line with the results of Alcántara et al. [22], who reported a value of 24.7. The mean C/N values for *Brachypodium* and the controlled spontaneous vegetation CC were equal to 26.9 and 25.1.

Regarding the aboveground residues, the percentages of the mean C release ranged from 40.5% to 48.3% (Table 5). The percentages of N and P release were higher than that of C in *Brachypodium* and controlled spontaneous vegetation. As shown in Table 5, the percentage of N release was very constant, varying from 45.8 to 47.5%. P release had a higher dispersion, ranging from 42.8% to 57.7%.

Table 5. Percentage of nutrient released per cover crop and year.

Cover Crop	Element [†]	Year				Average
		1	2	3	4	
<i>Brachypodium</i>	C (shoots)	72.4	32.8	29.2	33.2	42.2
	C (roots)	58.5	62.4	60.6	42.7	57.0
	N	87.5	25.3	28.4	35.2	47.5
	P	89.3	59.5	25.0	44.3	57.7
	K	96.9	70.6	75.8	73.2	80.8
<i>Sinapis</i>	C (shoots)	67.0	41.4	48.2	48.7	48.3
	C (roots)	53.6	51.0	59.2	41.5	51.0
	N	51.9	23.7	64.4	55.1	45.8
	P	51.6	16.4	62.8	47.9	42.7
	K	72.4	67.4	95.7	72.0	85.0
<i>Spontaneous</i>	C (shoots)	56.5	26.4	59.7	33.5	40.5
	N	70.1	23.0	71.9	20.7	46.0
	P	82.3	25.5	74.1	35.1	50.8
	K	94.6	83.5	96.7	56.9	90.4

[†] The percentage of nutrient released for N, P and K refers to aboveground residues.

Nevertheless, the percentage of K release was always noticeably higher than that of C, N and P. The fact that the K release rate was the fastest in the CC residues was mainly because most K exists in the form of ions and presents high solubility [64]. Thus, K is rapidly released through water digestion [43,65]. This release is an important contribution for soil and plants. On the other hand, C, N and P usually form organic compounds, which explain a different release mechanism [28].

The specific meteorological conditions were quite different every season (Figure 1), which had a significant influence on both the development in the growing stage and the decomposition after mowing. In the first season, all the CCs had lower biomass in the developing stage than in the second season. This scenario was reasonable since it was the installation year. Similarly, it is worth mentioning that an important daily rainfall event of 120 mm occurred in November 2007 in the growing season. This event caused substantial runoff and moved a proportion of the seeds, which reduced future plant density. The largest amount of biomass of all CCs was obtained in the second season. In the third season, excess rainfall in the autumn months, when the species emerged, significantly limited the growth of *Brachypodium*.

The carbon and nutrients released by the CCs during the decomposition period are depicted in Table 6. In comparison to the other CCs, the spontaneous CC had lower C, N and P release in the

decomposition process. This mainly occurred because the two new tested species produced a greater amount of aboveground dry matter residue after harvest, with 6691 kg ha⁻¹ yr⁻¹ (*Brachypodium*), 6171 kg ha⁻¹ yr⁻¹ (*Sinapis*) and 4839 kg ha⁻¹ yr⁻¹ (weeds). The moisture content (wet weight basis) in the residues was 48.6%, 30.7% and 33.7% for *Brachypodium*, *Sinapis* and weeds, respectively. C release from roots seems to be much higher in *Brachypodium* than in *Sinapis*, which is mainly explained by the differences in biomass in the developing stage and by the variation in the shoot to root ratio of the studied CCs.

Table 6. Amount released per cover crop and year, and total amount released along the decomposition cycles and the whole field experiment.

Cover crop	Amount Released (kg ha ⁻¹)	Year					
		1	2	3	4	Sum [†]	Global ^{††}
<i>Brachypodium</i>	C (shoots)	1974	1444.8	435.9	747.9	4602	10886
	C (roots)	2354.5	3923.5	1482.1	1461.9	9222	16175
	N ^{†††}	108.2	35.0	17.2	21.0	181	382
	P	10.0	12.6	1.9	4.3	29	50
	K	100.0	90.4	16.8	23.7	231	286
<i>Sinapis</i>	C (shoots)	1110.2	1875.5	856.2	964.5	4806	9945
	C (roots)	285.6	751.4	371.3	283.9	1692	3316
	N	24.2	29.4	65.1	33.8	152	333
	P	2.5	2.4	8.7	4.8	18	43
	K	10.8	37.1	131.2	16.4	195	230
<i>Spontaneous</i>	C (shoots)	516.2	834.9	1251.3	512.8	3115	7694
	N	19.9	25.2	83.2	9.5	138	300
	P	2.6	3.7	12.7	2.5	21	42
	K	42.8	73.6	131.5	7.7	256	283

[†] Sum of the amounts released in each decomposition cycle. ^{††} Sum of the amounts released in the whole experiment, from May 2008 to November 2011. ^{†††} The amount of nutrient released in N, P and K refers to aboveground residues.

The residue amount after harvest differed among species ($p = 0.008$), with the quantity in *Brachypodium* being significantly higher than that in the controlled spontaneous vegetation CC, while *Sinapis* did not differ significantly from the remaining CCs. It has been reported that spontaneous CCs usually produce less biomass than sown CCs [66]. However, the amount of K released was highest for the spontaneous CC in this research, at 256 kg ha⁻¹. This scenario occurred because the K concentration in spontaneous residues was 33% greater than the K concentration in the *Sinapis* and *Brachypodium* residues (Table 4).

In comparison to the other nutrients, P had the lowest content in the residue, so it was released in a lower amount. *Brachypodium* had the greatest P release, with 29 kg ha⁻¹. Although the N concentration in the residues was always higher than the K concentration, more K was released regardless of the CC because of its high solubility [67].

It must be highlighted that before sowing, *Sinapis* residues were buried by a disc harrow, which could have enhanced nutrient release in the growing stage of the new season [68]. However, *Brachypodium* and controlled spontaneous vegetation residues were not incorporated. They gradually decomposed during the following season, thus protecting the soil for a longer time. Assuming the residue of the previous season decomposes completely before the next mowing, the total amount of carbon and nutrients released will depend on the maximum biomass reached during the development period. In a four-season balance, *Brachypodium* potentially released the largest amount of carbon and nutrients from a global perspective (Table 6).

3.2. C, N and P Modelling

The relationship between residual C and aboveground residue amount is expressed in Table 7. This relationship was used to predict the C amount in the residues since it showed a coefficient of determination close to one. In all cases, the parameter β , which was equal to the increment in C amount per unit of increment of residue amount, was very similar. The intercepts were also similar. This implies a very similar C concentration in these herbaceous residues (Table 4), as reported by Ma et al. [62].

Table 7. Linear relationship between residual C and aboveground residue amount.

Cover Crop	Parameter	
	α	β
<i>Brachypodium</i>	−39.02	0.4128
<i>Sinapis</i>	−62.28	0.4238
<i>Spontaneous</i>	1.77	0.3948

Model: Residual $C_{i,t} = \alpha + \beta \times \text{Residue Amount}_{i,t} + \varepsilon_{i,t}$. The subscript i,t refers to sample i , measured in instant t . In all cases, $R^2 > 0.99$; p -value $< 10^{-10}$.

The relationship between the N and P amount in the residues with respect to the residue amount (not shown) was also significant but with a higher scatter. For this reason, k_N and k_P were determined according to Equation (8). The k_N was equal to $0.00014\text{ }^{\circ}\text{C}^{-1}$ for *Brachypodium*, $0.00026\text{ }^{\circ}\text{C}^{-1}$ for *Sinapis* and $0.00021\text{ }^{\circ}\text{C}^{-1}$ for the controlled spontaneous vegetation. Similarly, the k_P value was equal to $0.00018\text{ }^{\circ}\text{C}^{-1}$ for *Brachypodium*, $0.00029\text{ }^{\circ}\text{C}^{-1}$ for *Sinapis* and $0.00033\text{ }^{\circ}\text{C}^{-1}$ for the controlled spontaneous vegetation. This result implies that the release rate was, on average, always higher for P than for N. This was previously observed in pea under no-till farming [43]. Wang et al. [29] indicated that P and K in straw are released during short-term straw return, while C and N are released during long-term straw return. In our case, only K was clearly released in the short term.

The abovementioned coefficients k_N and k_P determined the rate of release. The higher the coefficient, the faster the element was released. Thus, P release rates were always higher than N release rates: 29% higher for *Brachypodium*, 12% for *Sinapis*, and 57% for the controlled spontaneous vegetation.

The predictions of decomposition according to the Rickman model varied among the different elements studied. Figures 2–4 show the experimental evolution of the C, N and P amounts in the aboveground residues throughout the four field campaigns. The figures also depict the results of the Rickman model with the corresponding adjusted k coefficient and its 95% confidence interval. Most experimental measurements were within the 95% confidence interval (Figures 2–4), ranging from 65% to 88% for the studied CCs.

The best E values were always obtained for C in all the CCs, ranging from 0.64 to 0.72 (Table 8). Similarly, the worst E values per CC were obtained for P in all cases, with values ranging between 0.28 and 0.44. The same pattern was shown by the coefficient r_{xy} , as shown in Table 8. This result means that the C residue amount was the best fitted variable, while P presented the worst fit. We hypothesize that this scenario could have been partially attributable to easily leachable P compounds [69]. At a global level, there was a slight overestimation by the models, which was manifested in seven out of the nine negative values of the CRM coefficient.

Pearson's linear correlation values between the observed and simulated values ranged between 0.62 and 0.84, with $p < 10^{-5}$ in all cases (Table 8). The sequence of the values of this coefficient was always $C > N > P$. Regarding the coefficient of efficiency and following the criterion of Van Liew and Garbrecht [60], the C, N and P amounts simulated by the Rickman model can be considered satisfactory ($0.36 < E < 0.75$) regardless of the CC, with the only exception being P in *Brachypodium* ($E = 0.28$).

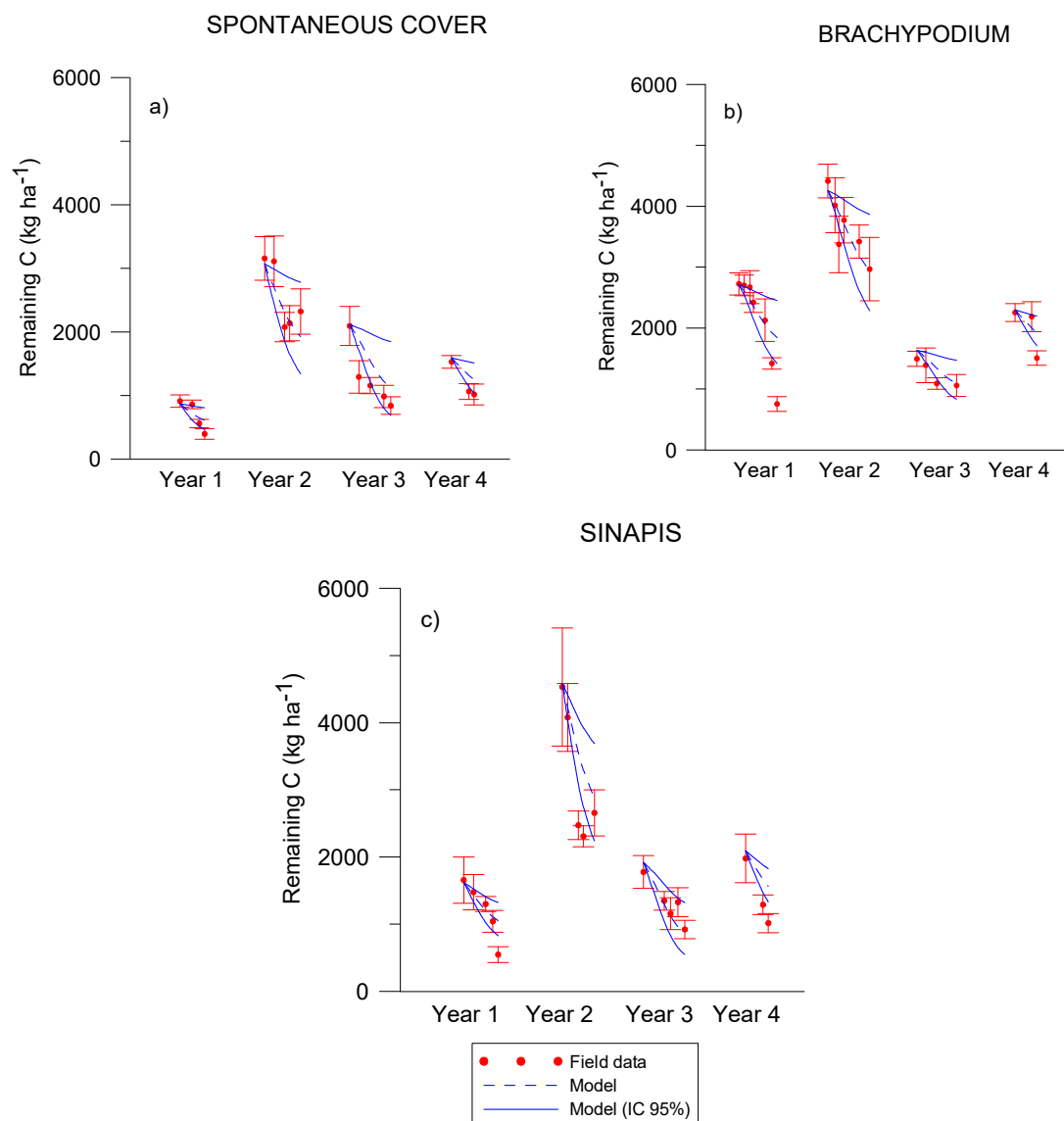


Figure 2. Measured and modelled C amounts in aboveground residues during the four decomposition cycles for spontaneous cover (a), *Brachypodium* (b) and *Sinapis* (c). The dashed lines represent estimations from the Rickman model [40].

Similarly, there was good agreement between the observed and simulated values in all CCs regarding the mean values (Table 8). The standard deviation of the observed values was always higher than that of the simulated values. This is logical since the models showed an expected value, i.e., a mean value. Nevertheless, the observed values exhibited great field variability.

This is a consequence of the short-distance natural variability in environmental variables [70,71], which is clearly evident when grab sampling is employed, as was the case here. However, grab sampling is a more realistic method than litterbags [33] since accessibility of the residues to decomposers can be limited by mesh openings. In addition, litterbags can alter the microclimate of the residues and put in contact with the soil some residues that would be standing for a long time period under natural conditions [36].

The Rickman model here exposed is an improvement of the Douglas–Rickman model, and has been extensively used with good results in a wide variety of climates and crops to predict decomposition or to aid in soil carbon modeling [41,43,45,72,73].

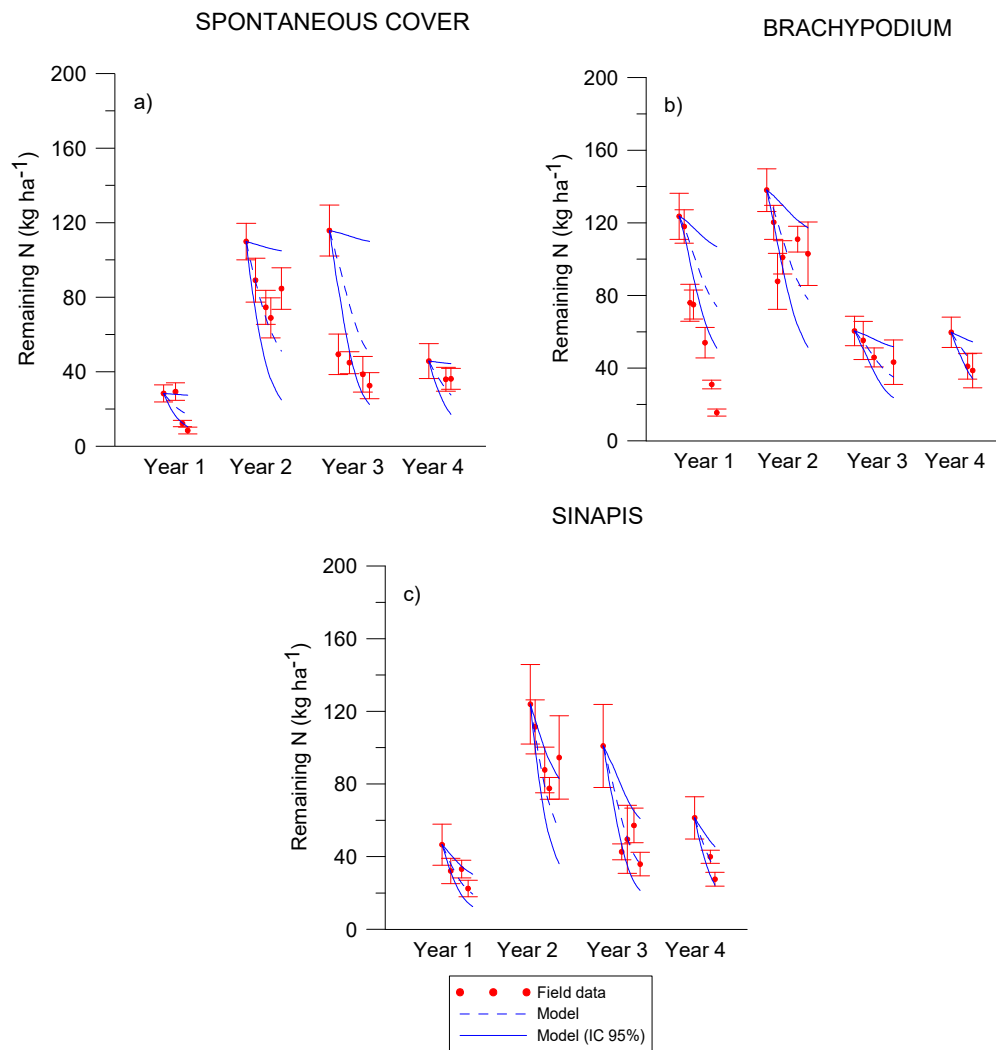


Figure 3. Measured and modelled N amounts during the four decomposition cycles for spontaneous cover (a), *Brachypodium* (b) and *Sinapis* (c).

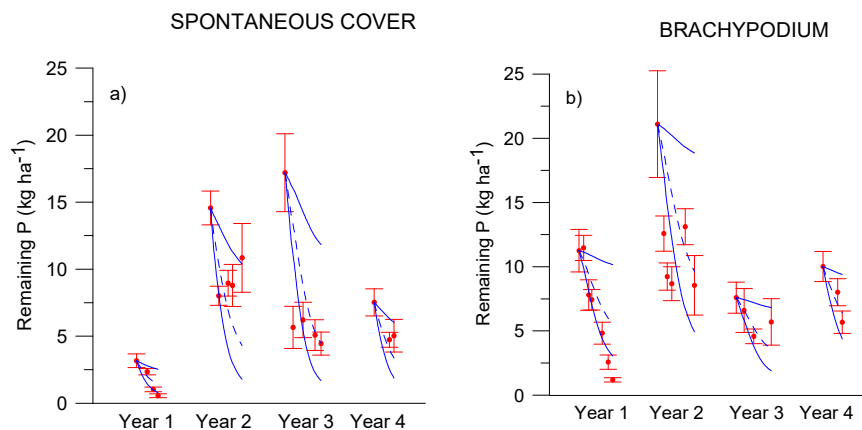


Figure 4. Cont.

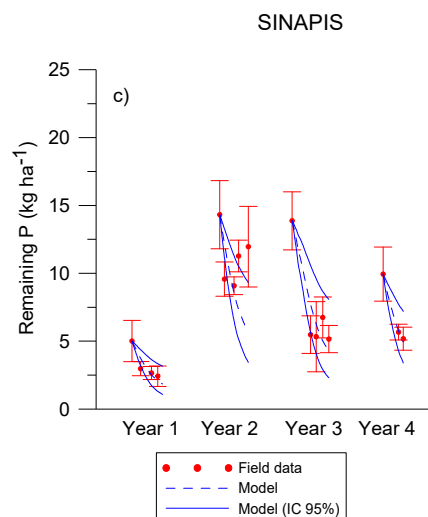


Figure 4. Measured and modelled P amounts during the four decomposition cycles for spontaneous cover (a), *Brachypodium* (b) and *Sinapis* (c).

Table 8. Coefficients for model evaluation and statistics obtained in simulations.

Species	Element				
			C	N	P
<i>Brachypodium distachyon</i>	Coefficient	E	0.69	0.38	0.28
		CRM	−0.02	−0.12	−0.14
	Observed values (kg ha ^{−1})	Mean	2433	76	8.8
		SD	1167	41	5.5
	Simulated values (kg ha ^{−1})	Mean	2493	85	9.9
		SD	898	31	4.7
	Correlation	r _{xy} ☆	0.84	0.67	0.62
<i>Sinapis alba</i>	Coefficient	E	0.64	0.54	0.37
		CRM	−0.12	0.08	0.08
	Observed values (kg ha ^{−1})	Mean	1815	60	7.2
		SD	1155	40	5.1
	Simulated values (kg ha ^{−1})	Mean	2039	55	6.7
		SD	1111	29	3.7
	Correlation	r _{xy} ☆	0.83	0.75	0.63
Spontaneous soil cover	Coefficient	E	0.72	0.50	0.44
		CRM	−0.10	−0.04	−0.01
	Observed values (kg ha ^{−1})	Mean	1503	54	6.8
		SD	900	39	5.1
	Simulated values (kg ha ^{−1})	Mean	1647	57	6.7
		SD	716	31	4.6
	Correlation	r _{xy} ☆	0.83	0.72	0.70

r_{xy}: Pearson's correlation coefficient. ☆ In all cases, correlations were significant, with $p < 10^{-10}$. E: coefficient of efficiency. CRM: coefficient of residual mass.

As seen in Figure 5a–c, the overall performance of the model applied to C, N and P is suitable. The slope is practically one in all cases, and the points are generally near the bisector, especially in the case of C (Figure 5a). In this element, the linear fit is always under the bisector, since the intercept was equal to -112 kg ha^{-1} . It is reflected in negative values of CRM (Table 8), ranging from -0.02 to -0.12 . Likewise, the highest coefficient of determination was obtained for C in all CCs, thus reflecting the best adjustment, which agrees with the highest E and coefficient of correlation for this element in all CCs. Similarly, the behavior of the model for N and P is also in line with the results in Table 8, with P being the worst fitted element.

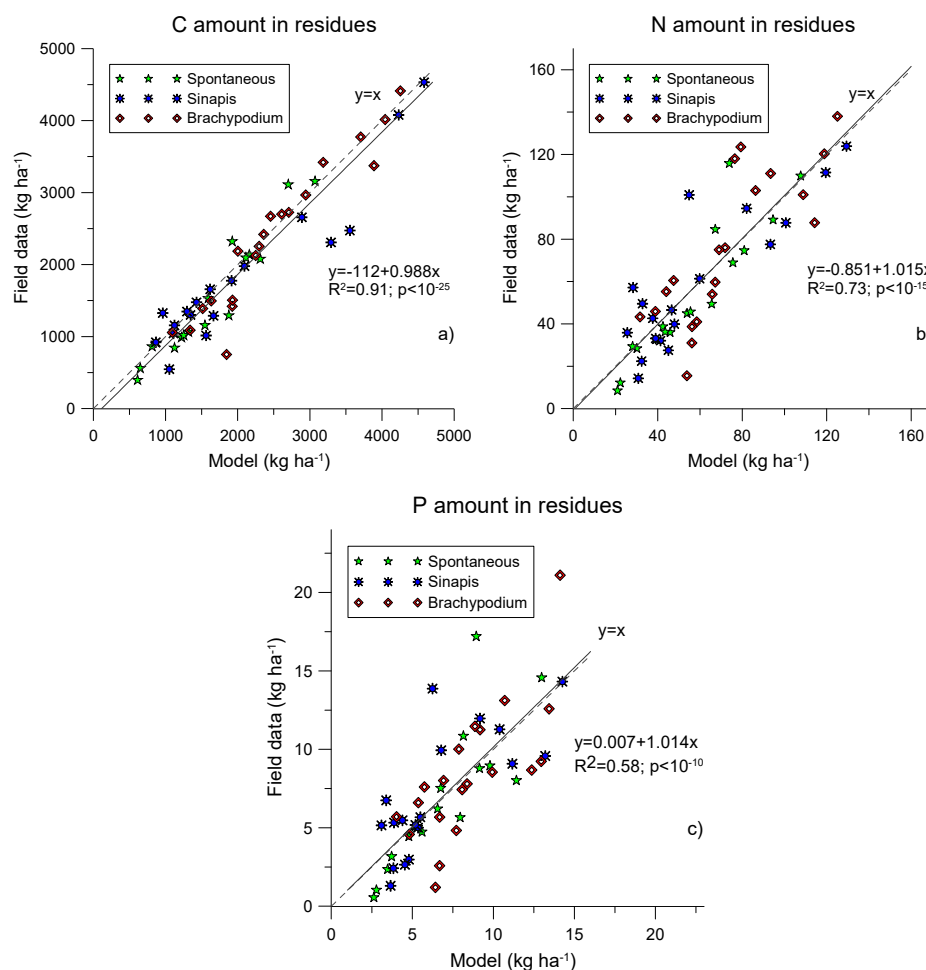


Figure 5. Measured versus estimated C (a), N (b) and P (c) amounts in the aboveground residues for the three types of cover crops and 4-year field trial. The dashed line is 1:1, and the straight line is the regression line.

The 95% confidence interval of the slope contained one in C, N and P. Therefore, the use of the Rickman model to determine C amounts, as well as simple exponential models for N and P, have proven to be adequate to predict the average C, N and P remaining in the aboveground residues under Mediterranean conditions.

4. Conclusions

The studied CCs released a large amount of C along the decomposition cycle, ranging from 0.8 Mg ha⁻¹yr⁻¹ to 1.2 Mg ha⁻¹yr⁻¹ in the aboveground residues. The release of C, N and P accounted for 42 to 57% of the total amount at the beginning of the decomposition cycles. The percentage of K release was always noticeably higher than that of C, N and P, ranging from 80% to 90% of the total amount in the CC residues.

The lowest amount of C, N and P released from residues was obtained in the spontaneous CC. It was mainly because it yielded significantly less residue after harvest than the newly proposed CCs. The opposite result was obtained for K, as the spontaneous CC increased K release by 11% with respect to *Brachypodium* and 31% with respect to *Sinapis*. Overall, the newly proposed CCs seem to be more promising for providing C and N to the soil than the spontaneous CC, which is currently the most used CC by farmers.

Under realistic field conditions, the Rickman model and the exponential model showed a good performance to predict C, N and P release from aboveground residues, with P being the worst fitted

element. These findings could help develop better practices under conservation agriculture and estimate nutrients release in olive groves.

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